CONSTRAINTS ON OUTER SOLAR SYSTEM EARLY CHRONOLOGY. T. V. Johnson[1], J. C. Castillo-Rogez[1], D. L. Matson[1], A. Morbidelli[2, 3], J. I. Lunine[4], [1]Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109 (e-mail address:Torrence.V.Johnson@jpl.nasa.gov), [2]Observatoire de Nice, Nice, France, [3]Southwest Research Institute, Boulder, CO, [4]Lunar and Planetary Lab, University of Arizona, Tucson, AZ.

Introduction: We address effects of the "Nice model" [1] in the outer Solar system. This model suggests that the "lunar cataclysm" was not confined to the terrestrial planet zone or the inner solar system, but should have been a solar system-wide phenomena, distinct from the last stages of accretion of the planets and satellites themselves. The "Nice model" suggests that this event was triggered by Jupiter and Saturn evolving into a temporary resonance, having the effect of pushing the orbits of Uranus and Neptune into the outer protoplanetary disk and gravitationally scattering large numbers of large icy planetesimals throughout the solar system while at the same time scattering planetesimals from the asteroid belt. This model can account for the magnitude of the LHB and its duration (50-150 My), as constrained from observations of the lunar cratering record [1, 2]. Moreover crater distribution at Mercury, Earth, Mars, and Vesta support the idea of a system scale event. Also, the "Nice model" provides a context for explaining outer planet irregular satellites [3], Trojans [4], and the formation of the Kuiper Belt [5]. The latter would have been produced during the same period as the LHB due to resonant effects between Neptune and Uranus. The Kuiper Belt would be the remnant of the massive disk from which originated the planetesimals that formed the outer Solar system.

We consider the implications of the "Nice model" regarding (1) the geological history of outer planet satellites and (2) KBOs properties.

Satellites Geological History: During the LHB satellites in the outer Solar system should have been heavily affected by intense bombardment. The oldest surfaces in the Saturnian system, especially Iapetus and Mimas, are expected to have recorded that event.

We are using models of the satellites' thermal histories to compute the capability of the satellites lithospheres to retain craters, depending on assumptions about their initial conditions, and especially the time of formation with respect to the production of calcium-aluminum inclusions (CAIs). Heat from short-lived radioisotopes (SLRI), especially ^{26}Al, plays an important role in decreasing the porosity in the least dense satellites and in fully differentiating the densest ones. Thus in turn it affects the ability of the early crust to record large impacts.

The comparison between the crater density on these surfaces with the current bombardment rate integrated over the age of the solar system will tell us whether or not the outer solar system underwent the so-called late heavy bombardment (LHB), characteristic of the Moon and the terrestrial planets.

Results for the outermost irregular satellite Iapetus were presented in Castillo-Rogez *et al.* [6]. Iapetus' cratered surface has multiple large basins, resembling, on a smaller scale, the lunar record [7]. There are two clues to establishing at least limits on the age of Iapetus' impact basins. First, the thermal history models that heat the satellite enough to accomplish despinning do not result in a lithosphere rigid enough to retain large basins for about 100 Myr after Iapetus forms. Second, at least one of the basins disrupts and therefore postdates a portion of the prominent equatorial ridge on Iapetus. The mechanism for forming this ridge is still not well understood, but [6] suggest that it may have been related to the surface area decrease and stresses associated with the de-spinning event, which occurs from 200 to 900 Myr after Iapetus' formation. While not establishing the exact age of the basins, these constraints suggest that these basins formed significantly later than the end of the satellite's accretion and are consistent with formation during the "Nice model"'s system-wide, late heavy bombardment at 3900 Ma.

Time relations are shown in Figure 1 based on the chronology of Iapetus' formation (with respect to the production of CAIs) proposed by [6].

Second-Generation Satellites: The "Nice model" suggests that satellites close to their planet are likely second-generation satellites. In the case of the Saturnian system, Mimas and Enceladus are good candidates for disruption as a result of the impact flux focusing toward Saturn. We argue though that Enceladus may have escaped complete disruption since it may have needed the heat from ^{26}Al decay in order to differentiate and provide hydrothermal conditions necessary to explain the South Pole geyser content of molecular nitrogen [8, 9]. We suggest that Enceladus' icy mantle could have been partially removed as a result of large impacts. This could explain its current relatively high density with respect to the neighboring satellites. In any case, the difference in crater distribution between Enceladus and Mimas indicates that resurfacing of the former occurred following the late heavy bombardment.

Composition of the Kuiper Belt Objects: Considering that the Kuiper-Belt objects are remnant planetesimals from the population that formed the outer Solar System satellite systems has important implications. We [6] have pointed out evidence that the outer Solar system formed a few My after the production of calcium-aluminum inclusions (CAIs). This is a reasonable scenario in view of the recent observations by *Spitzer* of young protoplanetary disks that cleared as fast as 1 My [10] and in about 3 My on average. If the planets in the early outer Solar system indeed formed in a few My, it is likely that planetesimals were strongly affected by ^{26}Al decay. The literature about carbonaceous chondrite parent body modeling (and especially Ceres, 11, 12] would be fully relevant to icy satellite modeling. We could expect that the icy planetesimals underwent differentiation, the smallest among them even subject to water boiling and loss. The Kuiper Belt and trans-neptunian objects show a wide range of physical properties. The largest ones, expected to be fairly compacted exhibit variations in density from ~1 g/cm^3 (Varuna, [13]) to 2.6 g/cm^3 (2003 EL61 [14]) while smaller KBOs have lower densities with both ice-rich compositions and high porosity. We could expect large KBOs to have formed early in the planetesimals belt. The presence of ^{26}Al would have resulted in early differentiation of these objects, and their disruption would have yielded objects enriched in rock or in ice (Cf. [15]). Thanks to the early accretion of ^{26}Al, the conditions might have been suitable for hydrothermal activity to take place, similarly to what is suspected to have occurred in Enceladus' early history, or in Ceres.

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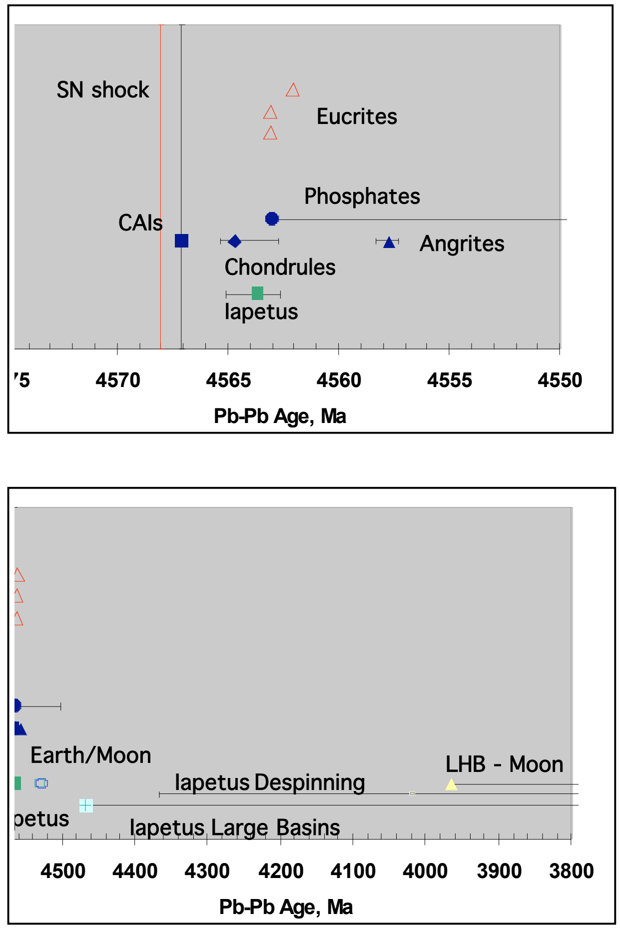

Figure 1. Solar system chronology (modified after [16]).